Introduction to Calibration and CALDB

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Calibration

Almost all of what we know comes to us through photons, which are deposited in a detector, causing an electrical signal that is measured and is then converted into physically meaningful quantities — aka *calibration*.

Calibration maps physics to data (and vice versa), forms a basic fingerprint of the instrument, and provides a framework to understand the data.

Outline

What are calibration products and where do they fit in?

- ARFs, RMFs, PSFs, etc.

CALDB

Calibration Data

Calibration data provide a quantitative characterization of *Chandra*'s detectors, optics, guide systems, and other spacecraft subsystems.

- The performance of the detectors and optics was measured pre-flight with absolutely calibrated detectors at NASA's Marshall Space Flight Center.
- Pre-flight calibrations provide the foundation for our understanding of the detector's performance.
- Calibration continues on-orbit via observations of on-board radioactive sources (ACIS), and fiducial astrophysical objects.
- *Chandra's* performance is compared with other X-Ray telescopes regularly.

Calibration Resources

- Main Cal page: http://cxc.cfa.harvard.edu/cal/
  - ACIS: http://cxc.cfa.harvard.edu/cal/Acis/detailed_info.html
  - HRC: http://cxc.cfa.harvard.edu/cal/Hrc/detailed_info.html
  - HETG: http://space.mit.edu/CXC/calib/hetg_user.html
  - LETG: http://cxc.cfa.harvard.edu/cal/letg/detailed_info.html
  - HRMA: http://cxc.cfa.harvard.edu/cal/Hrma/Index.html
- Calibration Status: http://cxc.cfa.harvard.edu/cal/summary/Calibration_Status_Report.html
- CALDB: http://cxc.cfa.harvard.edu/caldb/
  - Calibration Data: http://cxc.cfa.harvard.edu/caldb/calibration/index.html
- Cal Workshop proceedings: http://cxc.cfa.harvard.edu/ccw/tags/
- SPIE papers: http://cxc.cfa.harvard.edu/cda/cxo_papers/cxo_papers.html
- Cross-calibration (IACHEC): http://web.mit.edu/iachec/

The fundamental equation of observational astronomy

$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)$$

$$\times A(E;\mathbf{x}',t,\lambda)$$

$$\times P(\mathbf{x},\mathbf{x}';E,t,\lambda)$$

$$\times R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)$$

$$\times \Delta(t,t';\mathbf{x}',\lambda)$$

How incoming flux is distorted

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Normal}(\lambda,\sigma_\lambda)$$

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Poisson}(\lambda)$$

Observed quantity

$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

The astrophysical model

$f(\mathbf{x},E,t;\theta)$ [ph s^{-1} cm^{-2}]

$f_{\nu,\lambda}(\mathbf{x},E,t;\theta)$ [ergs s^{-1} cm^{-2}]

What arrives at the aperture of the telescope, from direction $\mathbf{x}$, with energy E, at time t, and is often modeled with parameters θ.

Watch out for those units!

$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

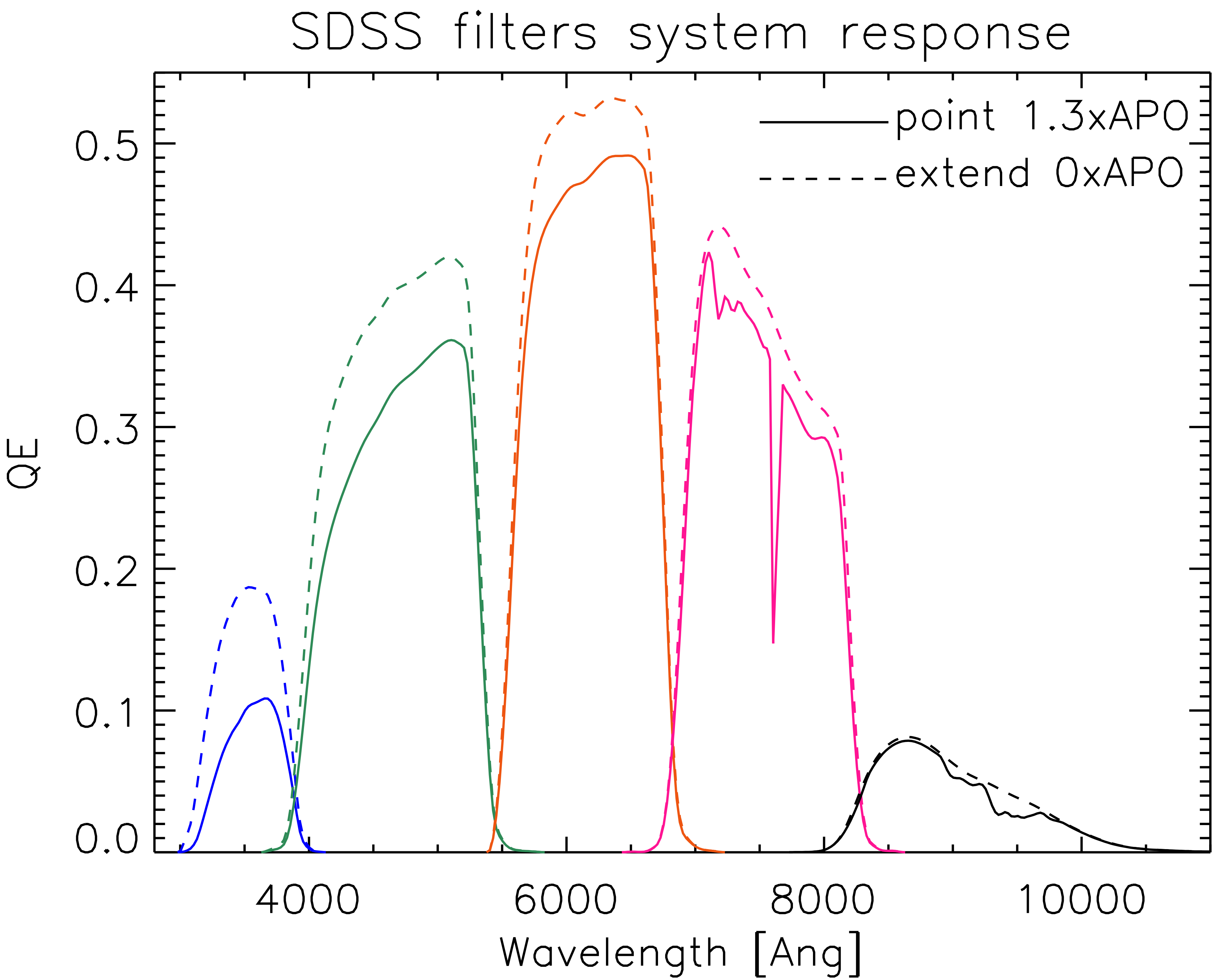
Effective Area

[cm^2 count/photon]

Describes the efficiency with which incoming photons are detected

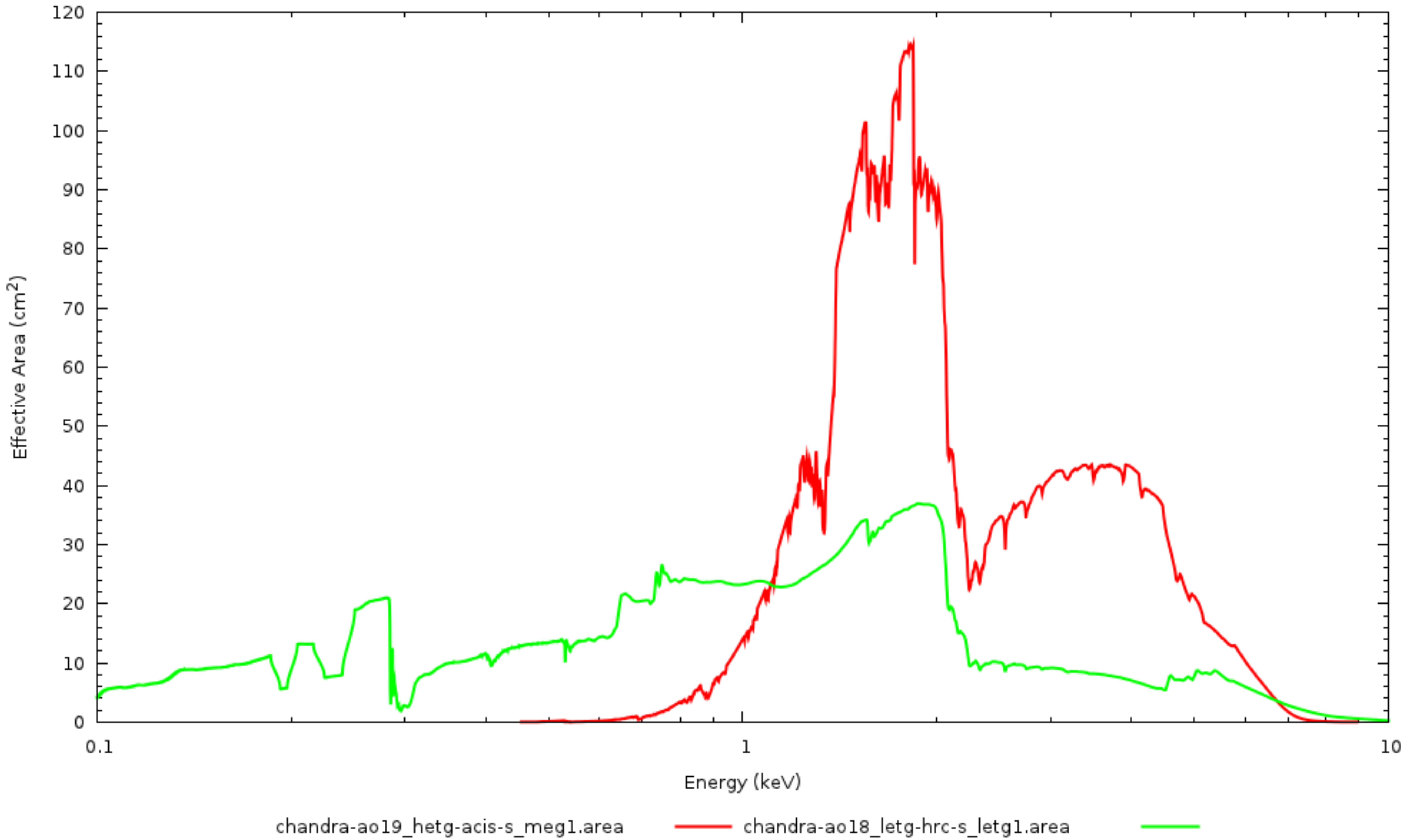
Mostly a function of photon energy E, but also depends on where on the detector $\mathbf{x}'$ the photon falls (and from what direction $\mathbf{x}$)

Can be affected by brightness of source via Pileup and UV leak (ACIS), gain non-linearity (HRC)



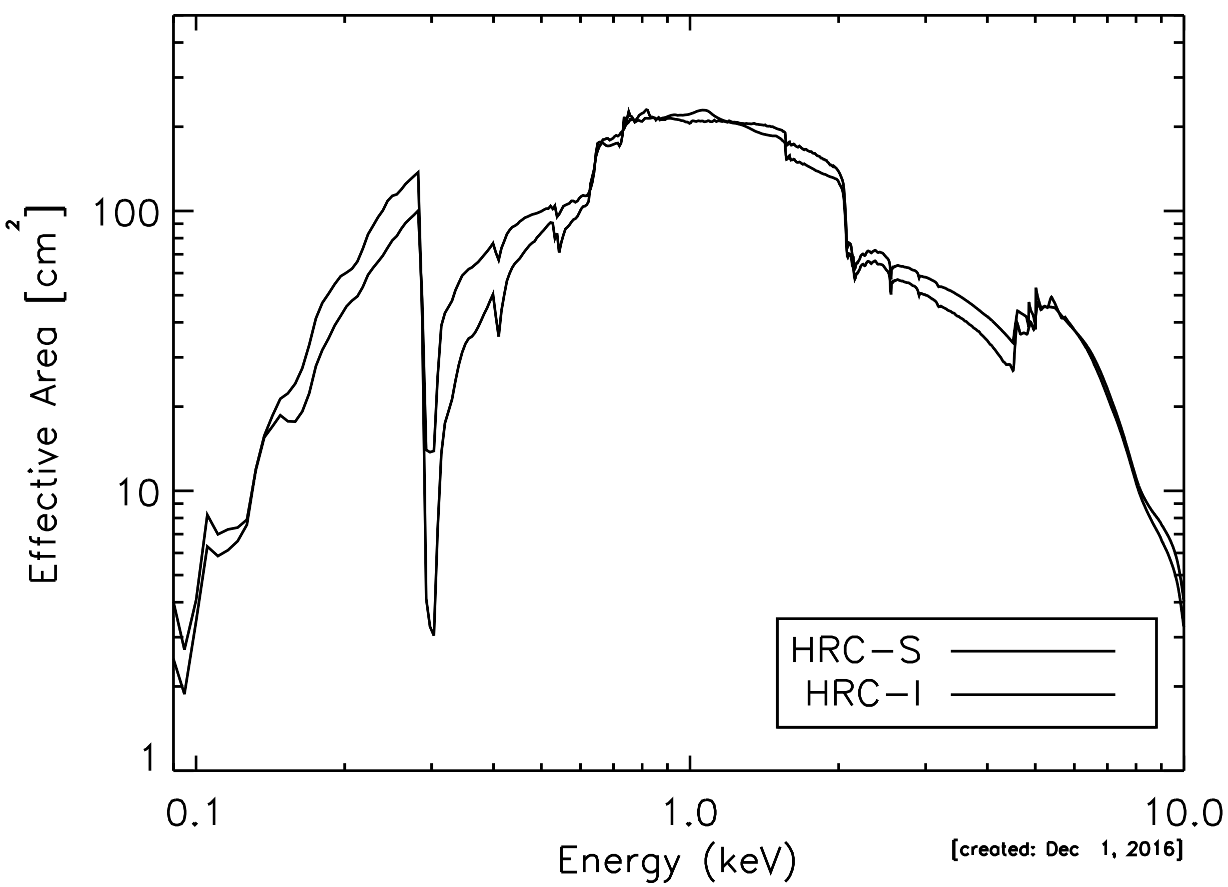
http://classic.sdss.org/dr3/instruments/imager/index.html

Chandra effective areas

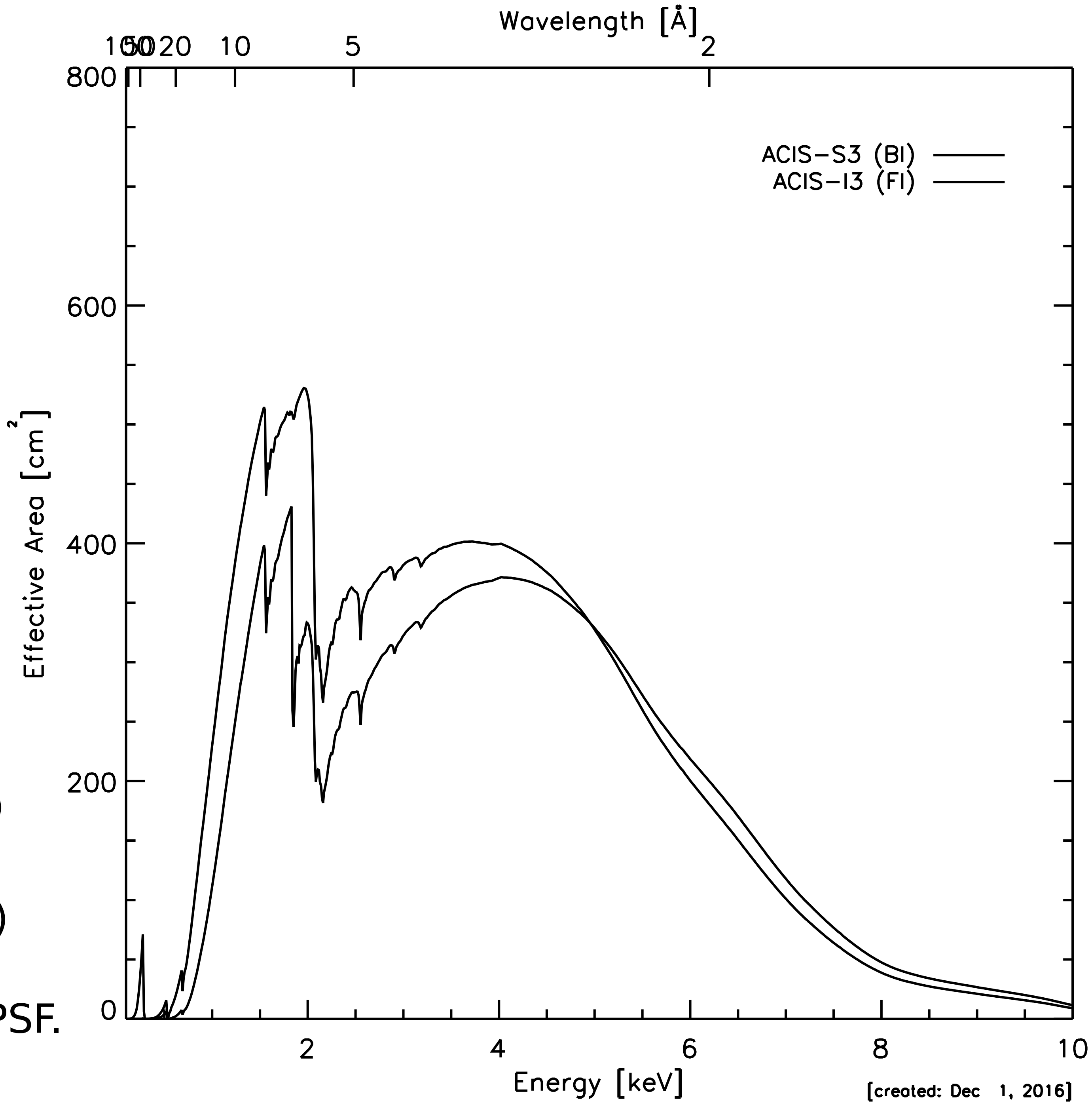


http://cxc.cfa.harvard.edu/cgi-bin/prop_viewer/build_viewer.cgi?ea

Chandra effective areas



The effective area of the HRMA/HRC-I (dashed line) and the central segment of the HRMA/HRC-S in imaging mode (solid line) integrated over the full PSF.



The HRMA/ACIS predicted effective area vs the energy. The dashed line is for the FI CCD I3, and the solid line is for the BI CCD S3.

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$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

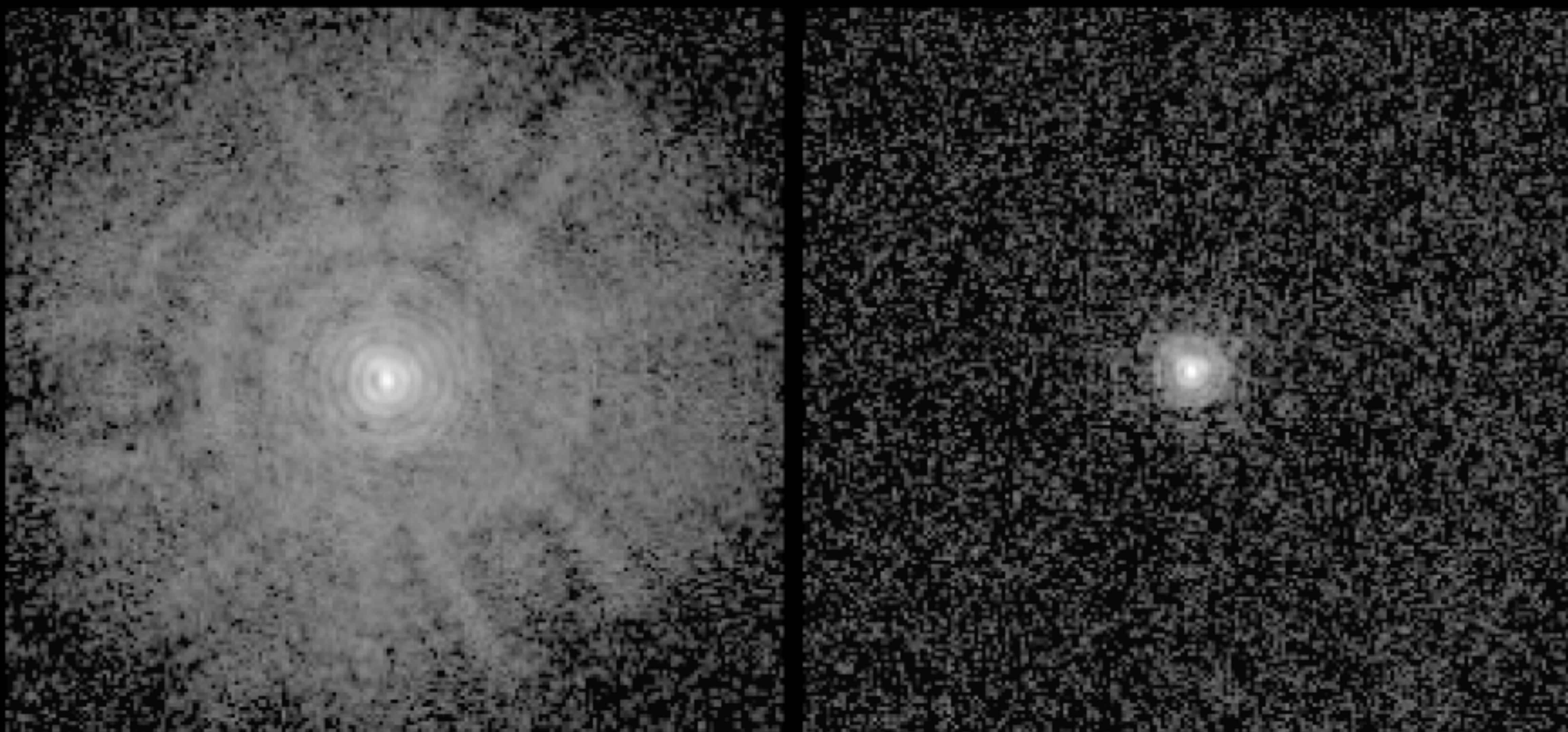
Point Spread Function

Describes the probability that a photon from direction $\mathbf{x}$ lands in detector pixel $\mathbf{x}'$

Energy dependent
Affected by mirror scattering
Distorted by pileup (ACIS)
and gain, degapping, and tailgating (HRC)

HUBBLE SPACE TELESCOPE

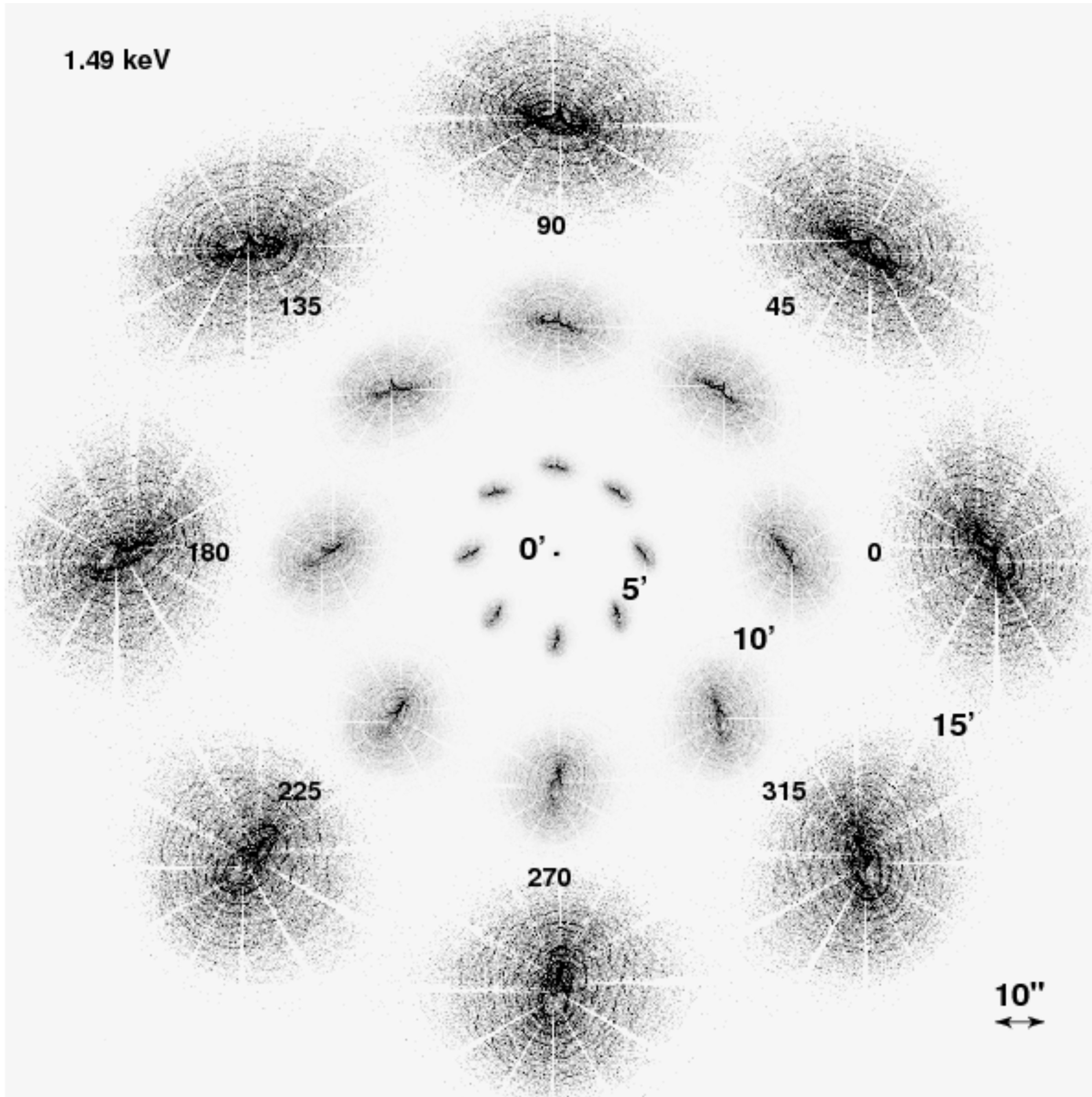
FAINT OBJECT CAMERA
COMPARATIVE VIEWS OF A STAR



BEFORE COSTAR AFTER COSTAR

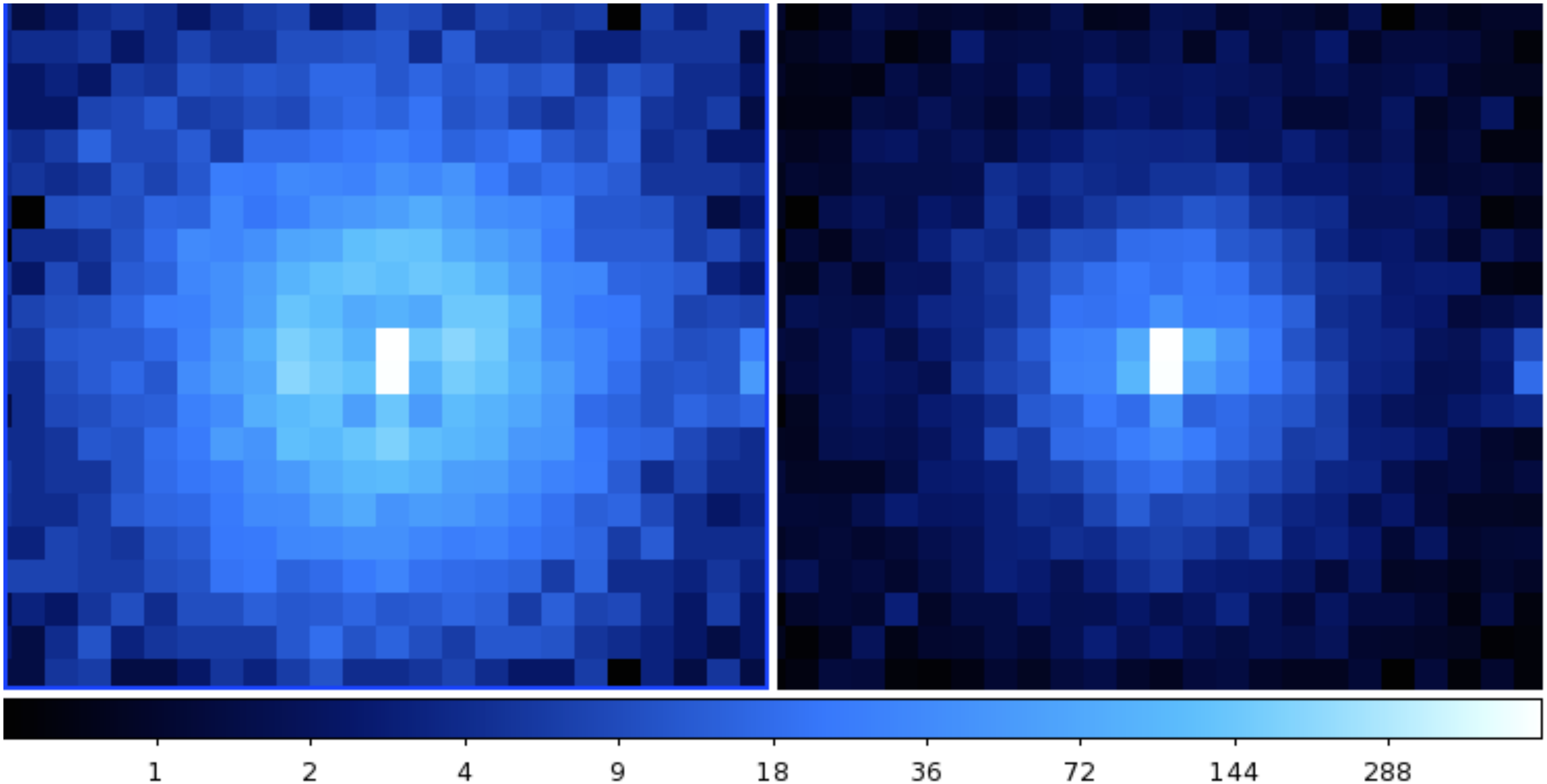
http://www.cv.nrao.edu/~pmurphy/images/astro/FOCpsfBW.png

Chandra Point Spread Function



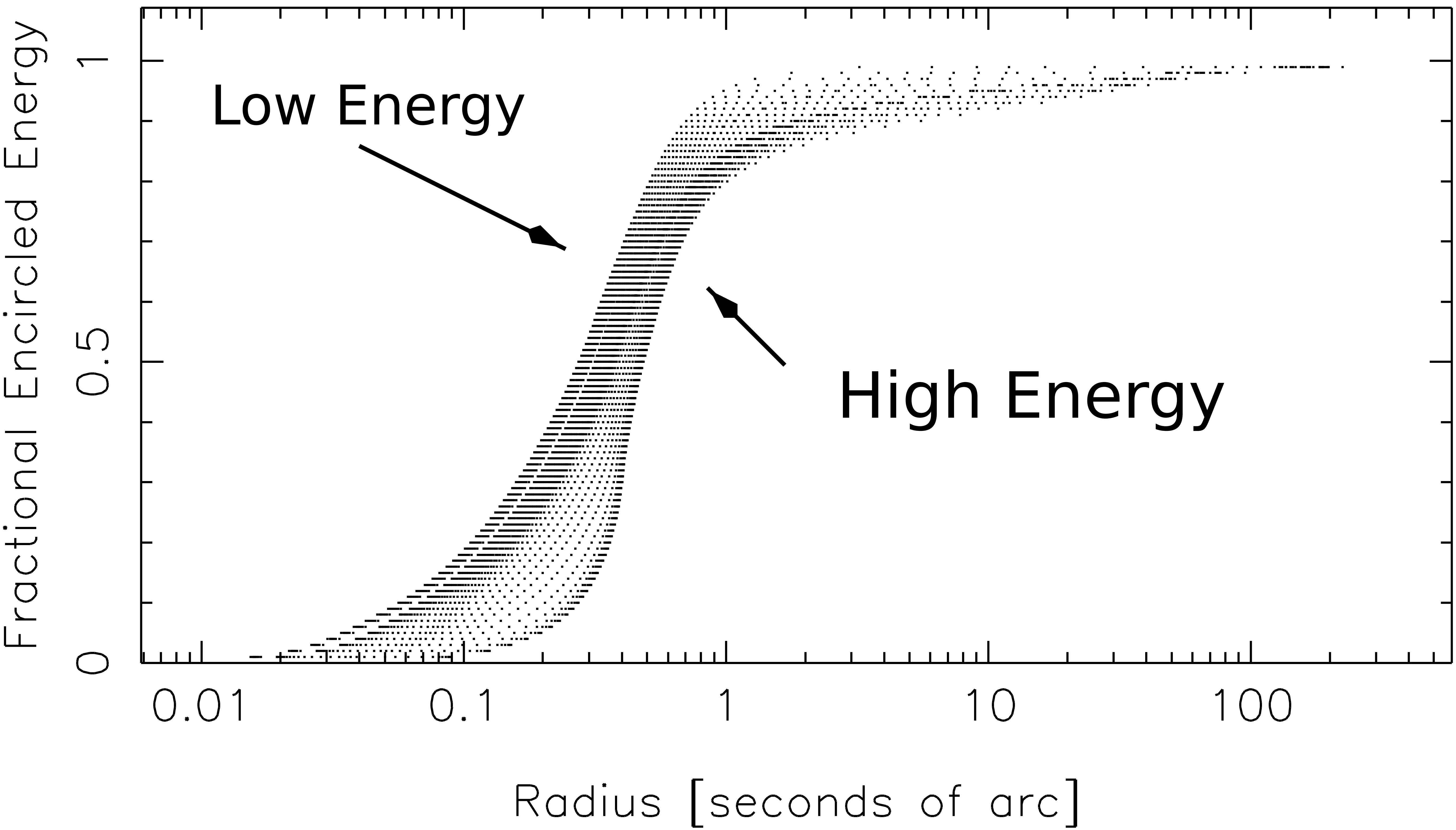
http://cxc.harvard.edu/proposer/POG/html/chap4.html#tth_fIg4.14

Effect of pileup



Counts image (left) vs flux image (right).
Pileup [http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf] changes spectral shape, sometimes leads to loss of photons.

Variation of on-axis PSF with energy



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$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda)P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

Spectral Response Matrix

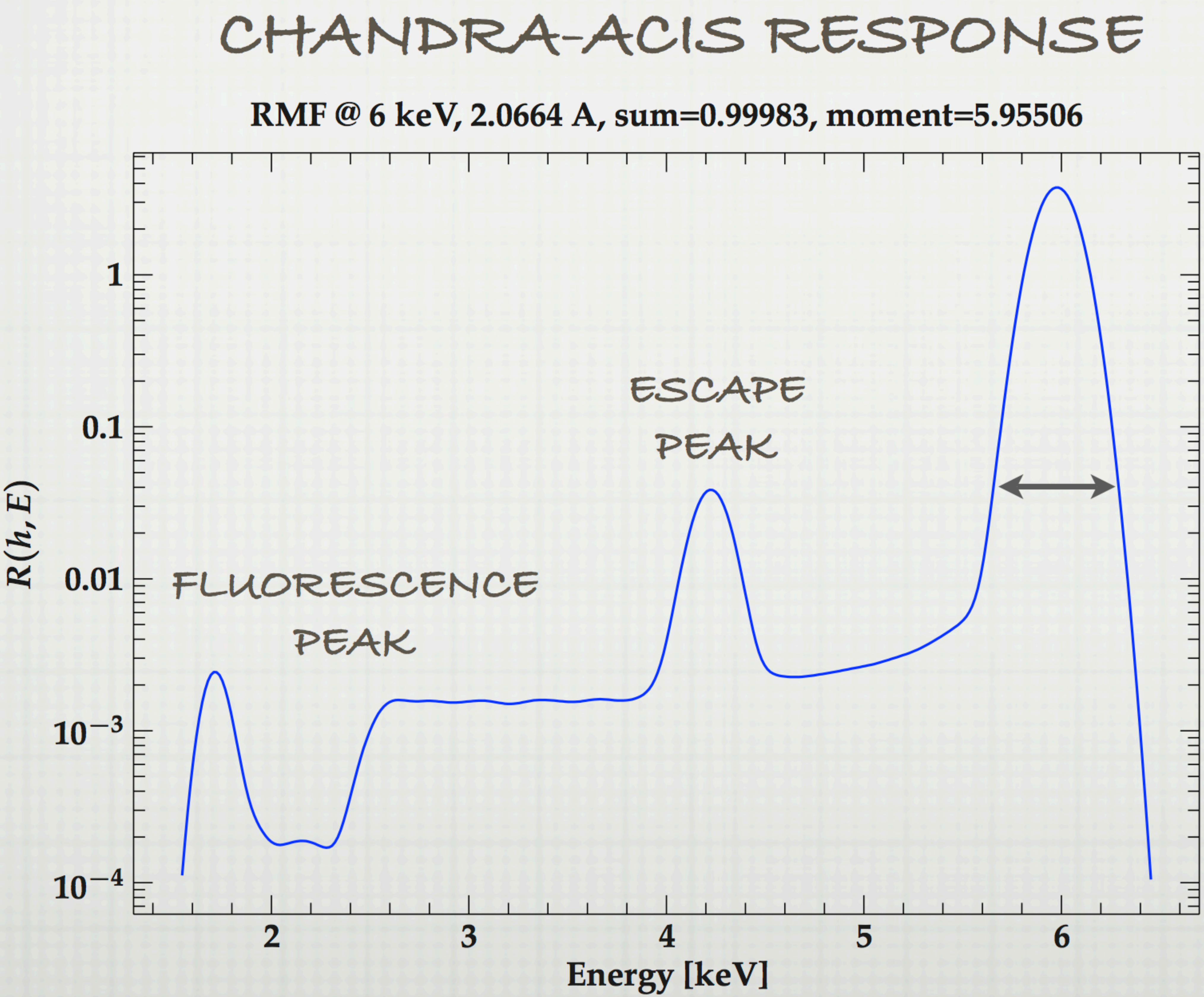
Describes the probability that a photon of energy E is recorded in detector channel E'

Think as probability; rows of matrix sum to 1.

Dependent on detector position due to QE and CTI (ACIS), and gain (HRC)

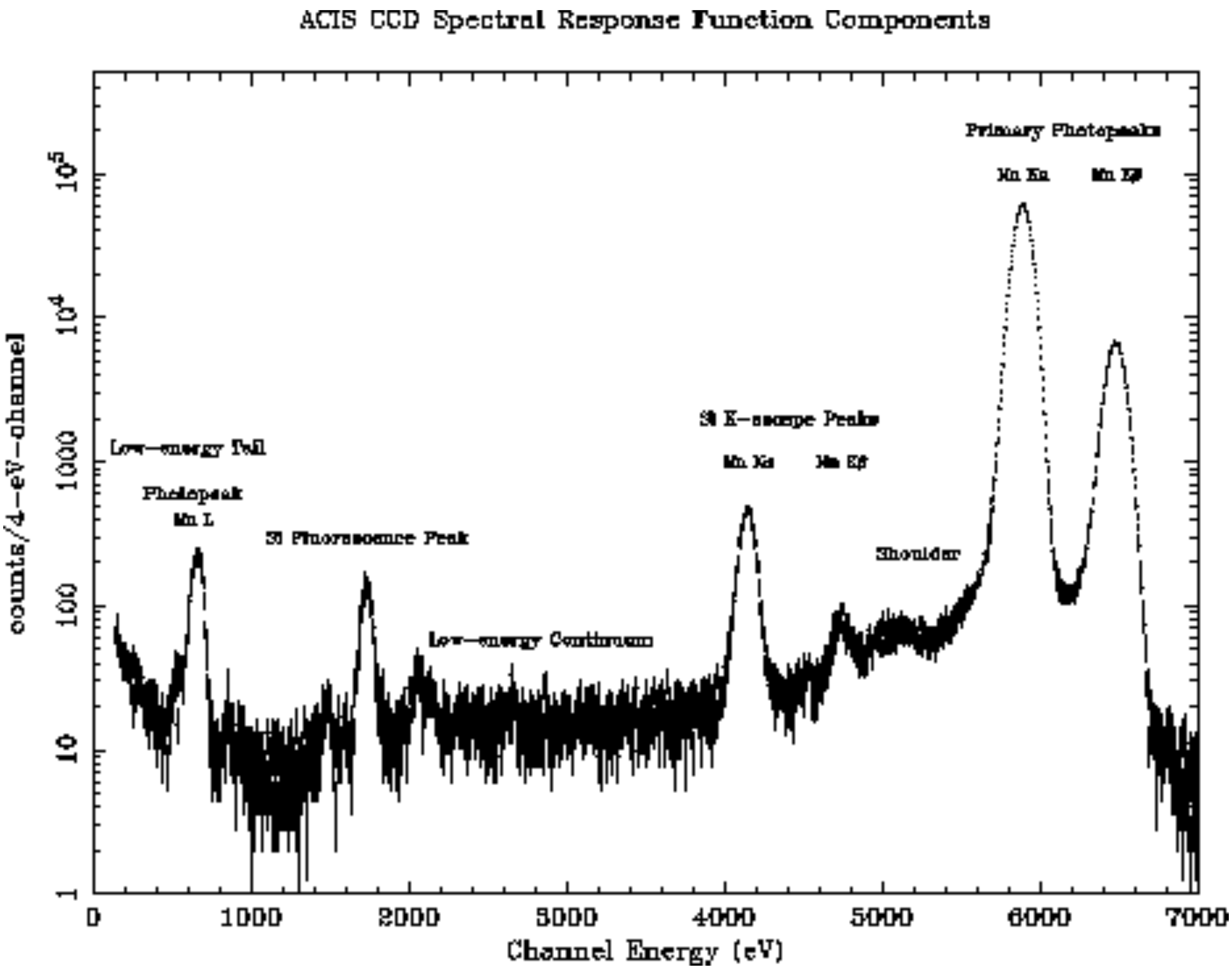
(in special cases (*Fermi*), also dependent on incoming photon direction)

Response Function (RMF)



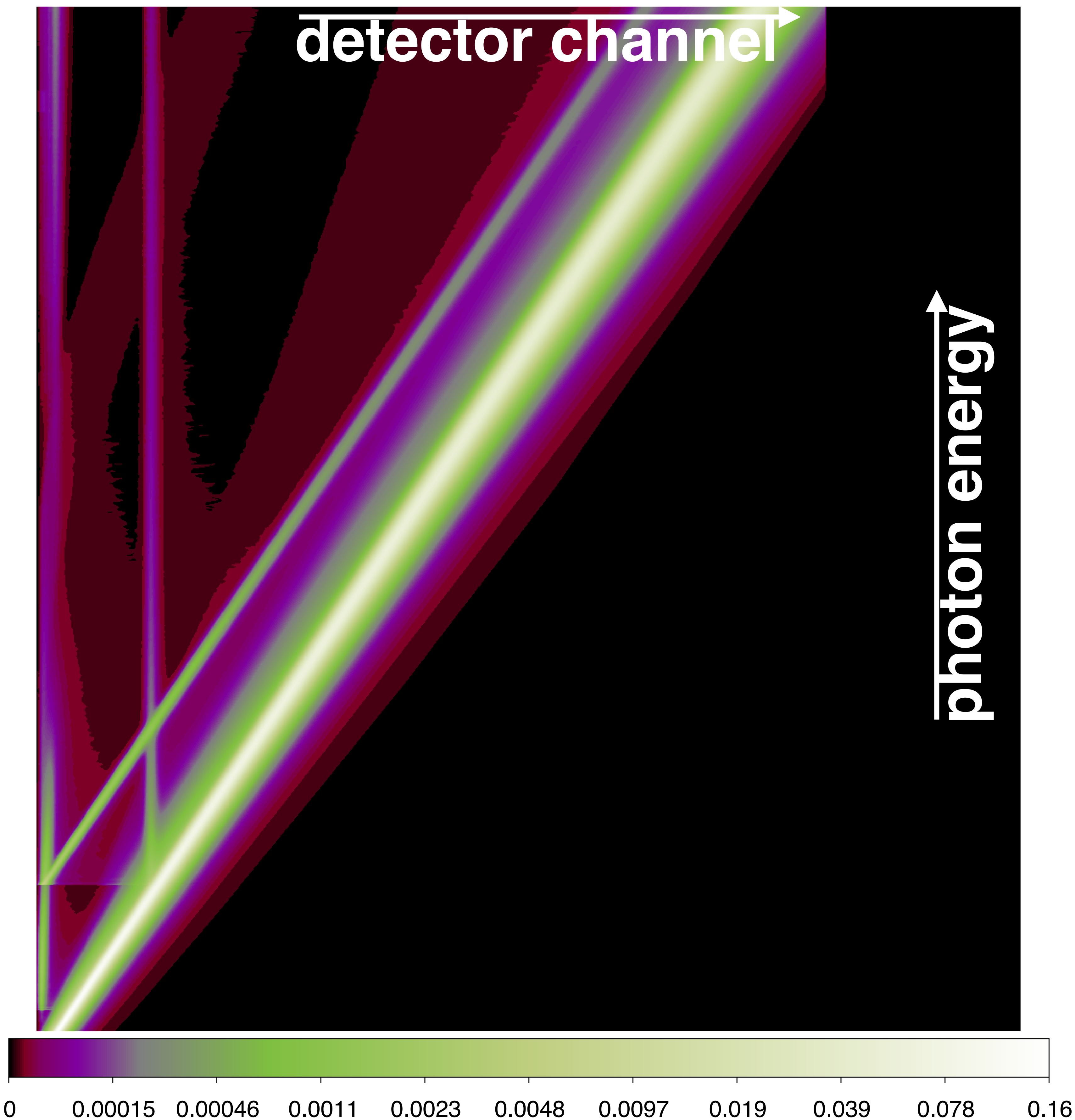
Mike Nowak

Chandra ACIS Fe^{55} calibration

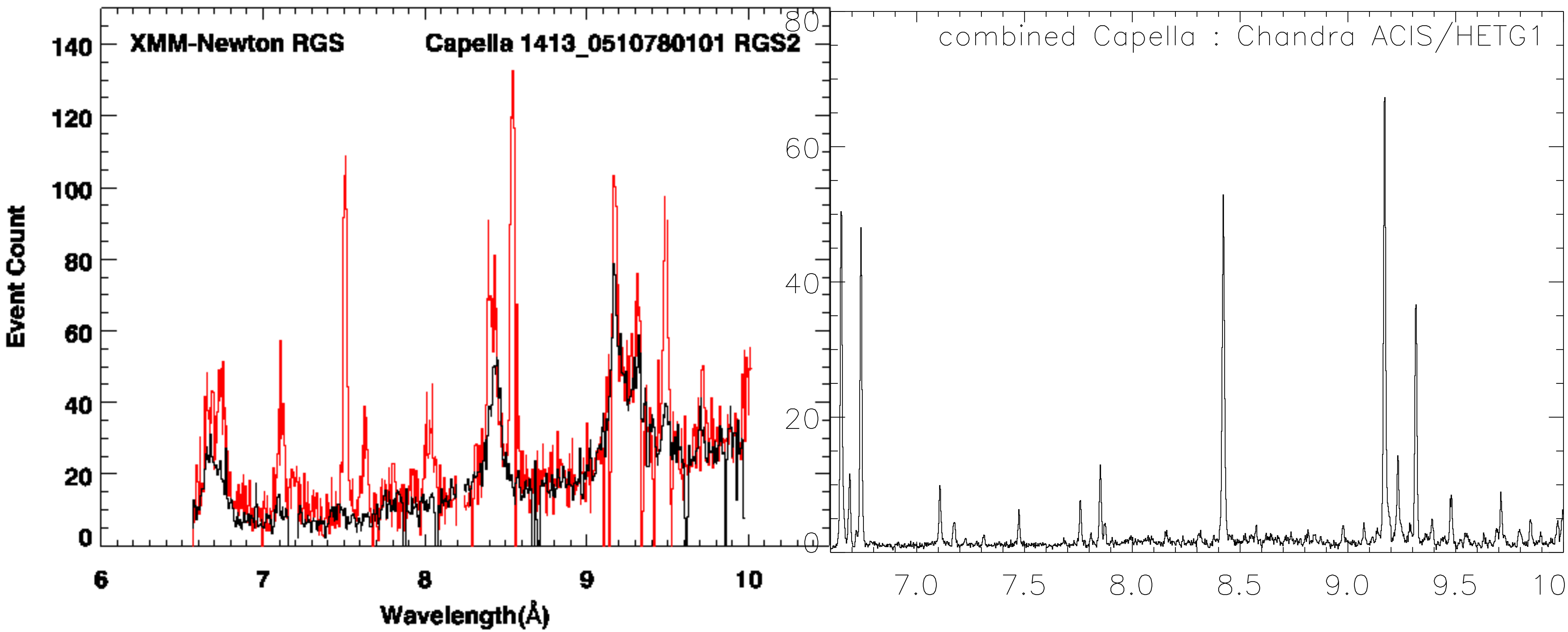


http://acis.mit.edu/acis/spie96/mb_calpaper/node3.html

Chandra ACIS-S RMF



Line Spread Function: Chandra vs XMM



For grating spectra, LSF is determined by PSF.

$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

Types of timing corrections:

frame time / integration time
resolution limited by readout cadence (ACIS)

dead time
when an event is detected, it takes a finite amount of time for the detector to “recover” (HRC)

Barycentric
to avoid time-of-flight effects on photon arrival times due to spacecraft position

The fundamental equation of observational astronomy

$$M(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)$$ incoming flux

Expected counts

$$\times\, A(E;\mathbf{x}',t,\lambda)$$ Effective area

$$\times\, P(\mathbf{x},\mathbf{x}';E,t,\lambda)$$ Point Spread Function

$$\times\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)$$ Spectral Response matrix

$$\times\, \Delta(t,t';\mathbf{x}',\lambda)$$ timing corrections

observed counts

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Normal}(\lambda,\sigma_\lambda)$$

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Poisson}(\lambda)$$

CALDB (*Cal*ibration *D*ata*B*ase)

The CALDB contains calibration data for Chandra and other missions

- is used by CIAO during processing and analysis
- is versioned, providing a traceable history of calibration data
- may be updated independently of CIAO — keep an eye on the chandra_announce mailing list to know when to update it

you may need to re-process newly acquired data after there has been a CALDB update (e.g., of ACIS gain or contamination)

When reporting results, indicate the versions of CIAO *and the* CALDB *which were used.*

http://cxc.harvard.edu/caldb/

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```
|-- data
|   `-- chandra
|       |-- acis
|       |   |-- badpix
|       |   |-- bkgrnd
|       |   |-- contam
|       |   |-- cti
|       |   |-- dead_area
|       |   |-- det_gain
|       |   |-- disp_reg
|       |   |-- evtsplt
|       |   |-- fef_pha
|       |   |-- grade
|       |   |-- grdimg
|       |   |-- gti_lim
|       |   |-- lsfparm
|       |   |-- osip
|       |   |-- p2_resp
|       |   |-- qe
|       |   |-- qeu
|       |   |-- subpix
|       |   `-- t_gain
|       |-- default
|       |   |-- aimpts
|       |   |-- axeffa
|       |   |-- geom
|       |   |-- greff
|       |-- default
|       |   |-- aimpts
|       |   |-- axeffa
|       |   |-- geom
|       |   |-- greff
|       |   |-- msidmap
|       |   |-- obi_tol
|       |   |-- reef
|       |   |-- sgeom
|       |   |-- sky
|       |   |-- tdet
|       |   |-- vignet
|       |   `-- wpsf
|       |-- ephin
|       |   |-- geom
|       |-- hrc
|       |   |-- amp_sf_cor
|       |   |-- badpix
|       |   |-- bkgrnd
|       |   |-- eftest
|       |   |-- fptest
|       |   |-- gaplookup
|       |   |-- gmap
|       |   |-- gti_lim
|       |   |-- lsfparm
|       |   |-- pibgspec
|       |   |-- qe
|       |   |-- gti_lim
|       |   |-- lsfparm
|       |   |-- pibgspec
|       |   |-- qe
|       |   |-- qeu
|       |   |-- rmf
|       |   |-- sattest
|       |   |-- t_gmap
|       |   |-- tapringtest
|       |   |-- tgmask2
|       |   `-- tgpimask2
|       |-- pcad
|       |   |-- align
|       |   |-- ccd_char
|       |   |-- ccd_resp
|       |   |-- cti
|       |   |-- dark_curr
|       |   |-- fdc
|       |   |-- gyro_sfma
|       |   |-- iru_char
|       |   `-- rwa_bspd
|       |-- pimms
|       |   |-- acis
|       |   |-- hrc
|       `-- sim
|           |-- det_pos
|           |-- det_poscorr
```

Using CALDB

- **check_ciao_caldb** — test your installation

```
CALDB environment variable = /soft/ciao-4.9/CALDB
          CALDB version = 4.7.6
          release date  = 2017-08-18T17:00:00 UTC
CALDB query completed successfully.
```

- **calquiz** — query the database for the right calibration file
- **download_obsid_caldb** — download all the calibration files relevant to processing your dataset
- **ardlib** — if you need to change your CALDB files, update ardlib.par (and remember to do punlearn ardlib after you are done to get back to default version)
- To trace the history of any calibration product, see http://cxc.cfa.harvard.edu/caldb/calibration/index.html

http://cxc.harvard.edu/caldb/

http://cxc.harvard.edu/caldb/

Limits of Calibration

Analysis results are only as good as the calibration data which they use

See the Calibration status Report[1] for an overview of calibration uncertainties

The PSF is not calibrated at the sub-arcsecond level. The EDSER algorithm for enhancing the PSF should only be used for qualitative analysis at this stage.

[1] cxc.harvard.edu/cal/summary/Calibration_Status_Report.html

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Calibration Resources

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    - HRC: http://cxc.cfa.harvard.edu/cal/Hrc/detailed_info.html
    - HETG: http://space.mit.edu/CXC/calib/hetg_user.html
    - LETG: http://cxc.cfa.harvard.edu/cal/letg/detailed_info.html
    - HRMA: http://cxc.cfa.harvard.edu/cal/Hrma/Index.html
- Calibration Status: http://cxc.cfa.harvard.edu/cal/summary/Calibration_Status_Report.html
- CALDB: http://cxc.cfa.harvard.edu/caldb/
    - Calibration Data: http://cxc.cfa.harvard.edu/caldb/calibration/index.html
- Cal Workshop proceedings: http://cxc.cfa.harvard.edu/ccw/tags/
- SPIE papers: http://cxc.cfa.harvard.edu/cda/cxo_papers/cxo_papers.html
- Cross-calibration (IACHEC): http://web.mit.edu/iachec/